Appendix D - Defining the "Saguaro Forest" on the Sonoran Desert National Monument

Introduction

The presidential proclamation establishing the Sonoran Desert National Monument (SDNM) provides direct expression that the monument "objects" are to be conserved, protected and restored for the benefit of current and future generations. The proclamation also expresses that livestock grazing may be allowed to continue north of Interstate 8 if grazing is compatible with the paramount purpose of the Monument, which is to protect the objects identified in the proclamation. The purpose of this study is to define the saguaro cactus (*Carnegia gigantea*) forests monument "object" and assess potential livestock impacts on it. A combination of remote sensing and field measurements were used to map and measure the saguaro forests within the SDNM north of Interstate 8.

Methods

The extent of the saguaro forest was defined through the use of remote sensing where four different sets of aerial and satellite imagery were acquired to manually map shadow casting saguaros using geographic information systems (GIS) software ArcMap 10.4. An effort was made to only use imagery that was taken during winter months where the sun was at a low angle thus casting long shadows behind the saguaro cactus. Over 0.5 million mature saguaro cactus were mapped, as points, on the SDNM north of Interstate 8. The point data was then rasterized at different cell sizes and the maximum saguaro per acre was defined for each raster. The maximum saguaro per acre for each raster was assessed to determine the most representative cell size to define the forest (Figure 1).

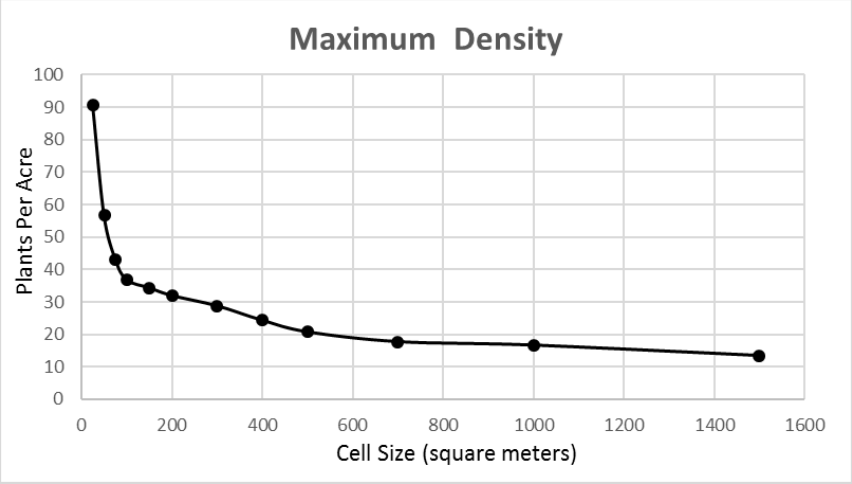
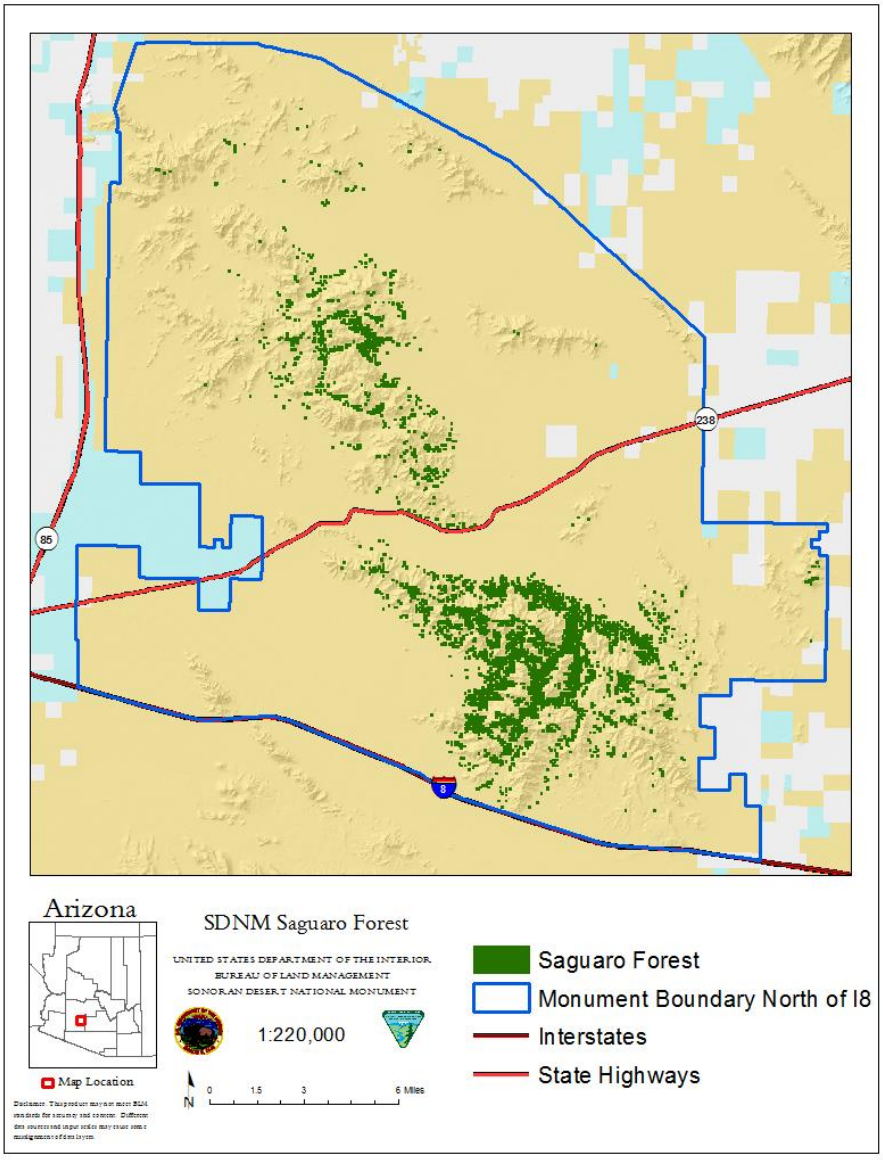


Figure 1. Maximum saguaro density for given raster cell sizes.

A cell size of 100 meters squared was identified to be the most representative of maximum saguaro density due to the exponential nature of the curve prior to this cell size. The average plants per acre for the 100 meter squared cell size was 8.7 plants per acre. Cells with less than 8.7 saguaros per

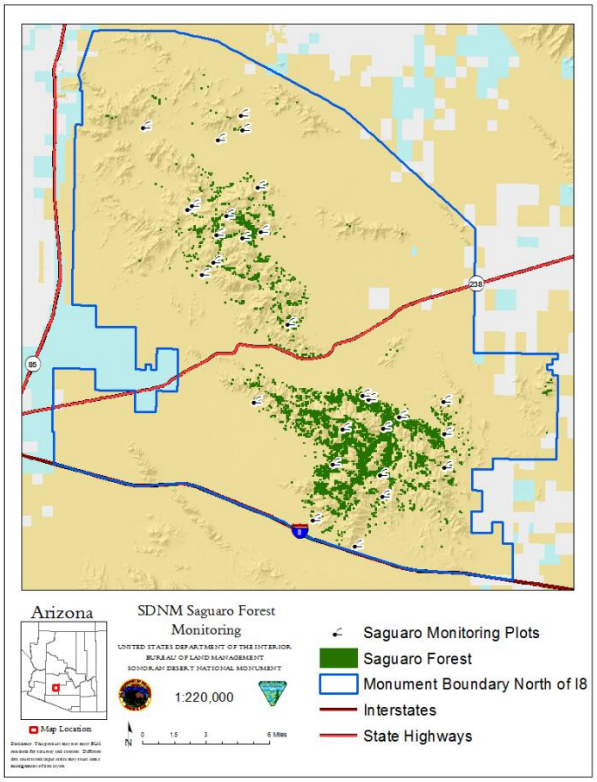
acre were removed from the raster leaving the preliminary saguaro forest extent. The preliminary extent included many isolated areas of saguaro that did not visually represent a continuous forest community due to great distances from other areas with at least 8.7 saguaros per acre. Therefore, the average 8.7 saguaros per acre was rounded up to 10 saguaros per acre which limited the number of isolated groups of cactus and produced a more continuous tract of saguaro forest (Map 1).



Map 1. Saguaro Forest

Following the identification of the extent of the saguaro forest, the attributes of the saguaro forest were measured using field monitoring plots (Appendix A). Plots were randomly stratified across the forest by grazing pastures with 3 plots per pasture. However, additional plots representing areas near (less than 2 miles) from livestock waters was needed and were randomly stratified in

these areas bringing the total number of monitoring plots to 28 (Map 2). Monitoring plots were one acre circles centered around a random point marked with an angle iron pointing north (Figure 2).



Map 2. Saguaro Forest Monitoring Plots

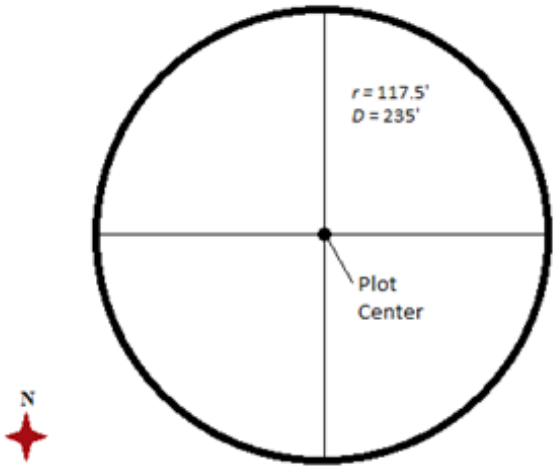


Figure 2. Saguaro monitoring plot layout

Starting from the plot center to 117.5 feet due north, saguaros were recorded in order as they were encountered while moving clockwise. As saguaros were encountered their height, number of arms, nurse plant, and health conditions were recorded. An effort was made to search under every shrub and tree for young saguaros. Plots were monitored between 2017 and 2020, 20 of which were monitored twice in that time period to determine growth and mortality rate.

The data was consolidated and an extensive literature review of studies documenting methods to determine saguaro age was conducted (Appendix B). Approximate saguaro age classes were developed where each saguaro was classified by height (Table 1).

Class	Height (ft)	Age (years)
Class 1	0-1	0-30
Class 2	1-5	30-50
Class 3	5-10	50-80
Class 4	10-20	80-130
Class 5	20+	130+

Table 1. Saguaro age classes

Saguaro plot densities were compared with geographic variables using scatter plot matrices, ordinary least squares, to check for potential correlation. Age classes of saguaro plots less than 2 miles were tested for significance using one tailed t-tests ($\alpha = 0.05$) against plots greater than 2 miles.

Results

A total of 771 live saguaros were recorded across the 28 monitoring plots. Age class distribution showed the majority of the population being represented by Class 4 and 5 saguaros totaling 75% of the sampled population (Figure 3). The 20 plots monitored in 2017/2018 and 2019/2020 showed a 3.4% mortality rate over 2 years. Ordinary least squares showed plot elevation to explain the majority (56%) of the variability of saguaro plot density (Figure 4). One tailed t-tests ($\alpha = 0.05$) show there to be significant difference ($p<0.05$) between the percentages of Class 1 and Class 2 saguaros between plots less than 2 miles from livestock waters and plots more than 2 miles from livestock waters. This indicates that the proportion of Class 1 and 2 saguaros is significantly less on plots near livestock waters versus plots far from livestock waters.

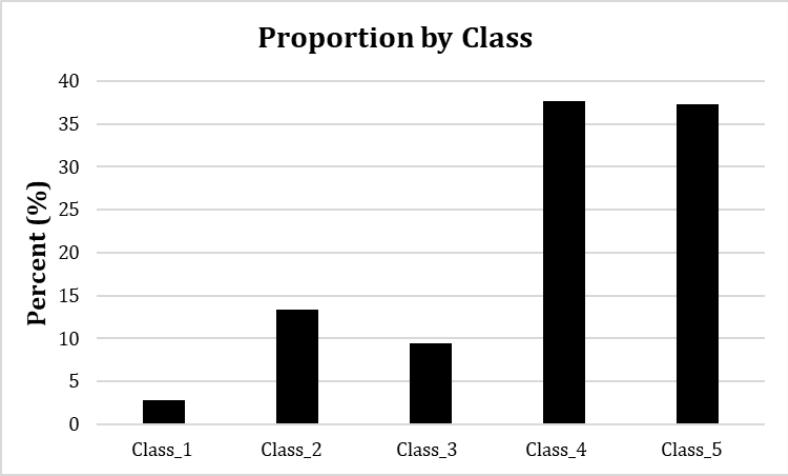


Figure 3. Proportion of saguaro forest by Class

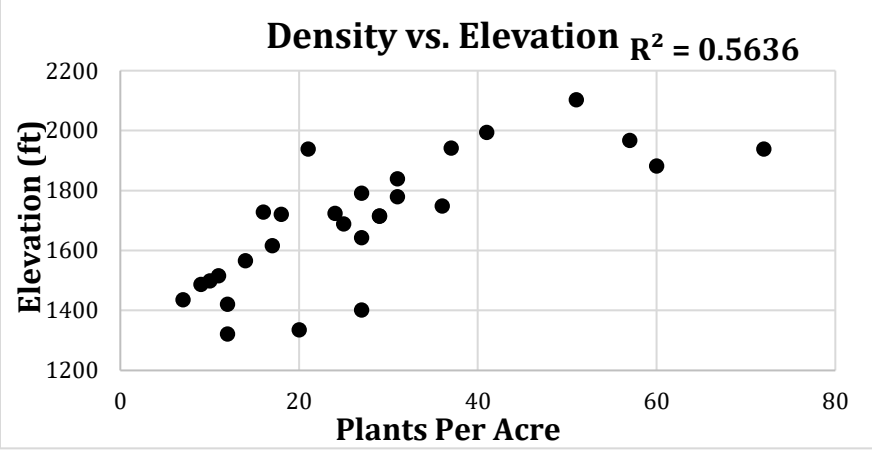


Figure 4. Density vs. Elevation scatter plot

Discussion

In this study, the saguaro cactus forests on the SDNM north of Interstate 8 were defined as an area of at least 100x100 meters (1 hectare) with at least 10 saguaros per acre (24.7 saguaros per hectare). In total, the forest covers 4,001 hectares or 15.4 square miles. The majority of the forest resides in the canyons and foothills of the Maricopa Mountain North and Maricopa Mountain South Wilderness areas.

The results of this study indicate that saguaro population is primarily comprised of older individuals which have exhibited a mortality rate of 3.4% over two years. This mortality rate is not considered abnormal when compared to other saguaro studies (Orum et al. 2016). No catastrophic weather events such as extended drought or strong freezes occurred between 2017 and 2020. This mortality rate largely shows the natural attrition of old saguaro cactus.

The density of saguaros on the SDNM increases as elevation increases which is likely due to the collinear relationship of elevation, precipitation and rocky terrain. This result is consistent with other studies conducted on saguaro cactus on sites across Arizona (Steenbergh and Lowe 1983).

This study also indicates that livestock grazing over the past 50 years may have contributed to the reduction of saguaro recruitment in areas within two miles of livestock waters. This may be due to trampling and/or the removal of nurse plant species for which saguaros rely on for germination (Steenbergh and Lowe 1983; Ahnmark and Swann 2008; Drezner and Balling 2008). However, no obvious direct impacts on saguaros from livestock were observed during the monitoring of plots. Of the 4,001-hectare saguaro forest, 22% of the forest is inaccessible to livestock due to slope (30%) and terrain (rockiness) limitations which prevents livestock movement in the area (Mueggler 1965). Only 15%, 589 hectares, of the saguaro forest are within 2 miles of livestock waters.

To improve this study, additional data should be collected to calculate the true growth rate and therefore the true age of the saguaros. It is likely that the saguaros of the SDNM grow at a much slower rate, due to less annual precipitation, than other studied populations. This would provide a more accurate representation of the age of the saguaro stand. A long-term analysis of geographic variables and climate change may also provide new insights on factors influencing the recruitment of saguaros on the SDNM.

Literature Cited

Ahnmark, E.B. and D.E. Swann. 2008. A history of saguaro cactus monitoring in Saguaro National Park, 1939-2007. Natural Resource Report NPS/SODN/NRR-2009/093. National Park Service, Fort Collins, Colorado.

Drezner, T.D. and R.C. Jr. Balling. 2008. Regeneration cycles of the keystone species Carnegiea gigantean are linked to worldwide volcanism. Journal of Vegetation Science. 19:587-596.

Mueggler, W.F., 1965. Cattle distribution on steep slopes. Journal of Range Management. 18:255-257.

Orum, T.V., N. Ferguson, and J.D. Mihail. 2016. Saguaro (*Carnegiea gigantea*) mortality and population regeneration in the cactus forest of Saguaro National Park: Seventy-five years and counting. PLoS One. 11(8): e0160899. https://doi.org/10.137/journal.pone.0160899.

Steenbergh, W.F. and C.H. Lowe. 1983. Ecologcy of the saguaro: III growth and demography. Department of Interior National Park Service. Washington, D.C.

Appendix A - Saguaro Forest Density Monitoring Protocol

Materials

-1x 2ft 1x1inch angle iron

-1x hammer

-1x compass

-1x GPS device

-1x Clinometer

-1x Camera with extra batteries

-3x 300ft tapes

-1x 6ft pvc pipe measuring pole (with attached decimal-feet measuring tape)

-Flagging

-Clipboard/ photo board

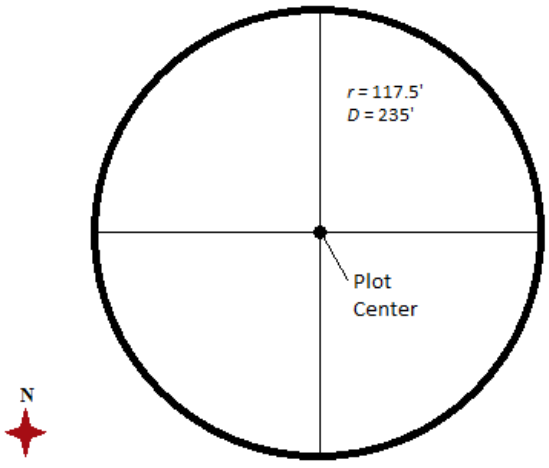
-Saguaro data recording forms

Site Setup

Navigate to the provided coordinates. The coordinates will serve as the plot center. Hammer the angle iron into the ground at plot center with the angle pointing north. Before setting up equipment, take pictures of the study location. Take five pictures total, one is an up close of the photo board, and the rest are landscape shots from each cardinal direction starting with north and moving clockwise.

It is important that the photos are taken with attention to detail. The angle iron and photo board should be centered in the frame. It is important to capture the tops of the saguaro with little sky above them. The photo should be in focus and free of loose gear (i.e. backpacks, tapes, hammers, personal items etc.)

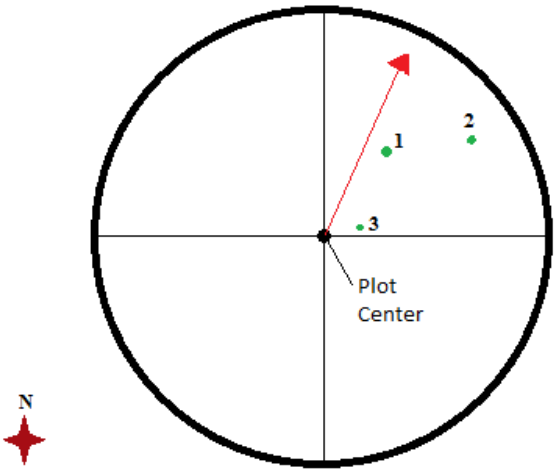
Once the pictures are taken, use two 300 foot tapes to measure out the plot. The plot diameter is 235 feet (i.e. 1 acre). The tapes are run north to south and east to west 235 feet with the plot center at the 117.5 foot mark. This sets up a full acre study site.



Once the plot is established, use the flagging to mark all the saguaros located within the plot. Each saguaro growing within the plot should be flagged with surveyors tape before being read, making sure to search thoroughly for young plants hiding in litter or under nurse plants. Use the third 300 foot tape to measure any saguaros growing on the plot edge to make sure all and only those saguaros growing within the plot are recorded. A saguaro is considered in the plot if its center is within 117.5 feet from the plot center.

Starting from the north line, the reader records the height, health status, and number of arms of each saguaro, in order moving clockwise (as if the plot was the face of a clock and recording each saguaro as the second hand would encounter them). Dead or downed saguaros should be counted in order of occurrence but not measured for height. However, down saguaros should only be counted if the rooting location is clear. This discounts those that have been moved by environmental factors like flooding.

As the information for each saguaro is recorded, the surveyors tape should be removed and packed up for later use or disposal. This helps ensure that a single saguaro is not recorded twice. Once the entire plot has been read, the tapes should be rolled up and all equipment packed out except for the permanent angle iron plot marker.



The order by which individuals saguaros should be recorded on the data sheet (as if the plot was the face of a clock and recording each saguaro as the second hand would encounter them).

Measuring Height

Height is always measured to the top of the tallest part of the plant, either the trunk or tallest arm. Always measure height from the upslope side. Saguaros under 6 feet tall can be measured using the 6 foot pvc pole with the attached decimal-feet measuring tape. Height is taken at the tip of the spines. Saguaros taller than 6 feet must be measured using the clinometer. The clinometer used for the initial monitoring year is a Haglof EC II-D Electronic Clinometer. This digital clinometer requires three separate measurements to calculate height. The first measurement is taken at the base of the saguaro. The second measurement is taken at exactly 6 feet height which can be determined using the 6 foot pvc pole situated at the base of the saguaro. The last measurement is taken at the top of the saguaro. When taking these measurements it is important make sure there is enough distance between the saguaro and the reader to get an accurate height. A general rule is to stand far enough away from the saguaro that, if it were to fall over, it would not hit the reader.

To use the digital clinometer, first click the "on" button twice at a steady pace, with one second in between clicks. "DEG" will appear on the screen. Once "DEG" is shown on the screen, aim the clinometer at the base of the saguaro. Click and hold the "ON" button until there is a single beeping noise. This indicates that the angle has been recorded. Next, aim at the 6 foot reference mark and hold the "ON" button again, until there is a beep. Last, aim at the top of the saguaro and repeat. Once all three measurements are taken, the calculated height of the saguaro will appear on the screen.

Counting Arms

Arms should only be counted if they have distinctive pleats(ribs) present. Nubs that have not formed pleats are not included. Sub-arms that are growing off of other arms should be included in the overall count. Saguaro arms that are broken or have fallen off should be counted, but indicated as such on the data sheet.

If there is no clear separation at the base of what appears to be two or more saguaros growing very closely, they are counted as a single plant with a basal split (schoolmarm). The tallest is measured as the saguaro height and the others are counted as arms.

Schoolmarm: no discernable separation

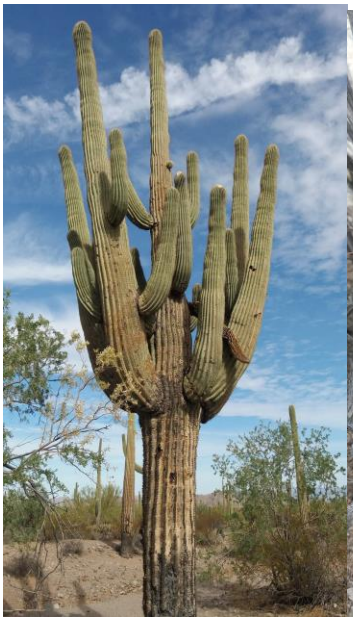
Nurse plants

For a nearby growing plant to be considered a nurse plant it must shade, cover, or touch the saguaro. Plants that do not fall into one of these categories should not be recorded. If more than one plant species may be considered a nurse plant by the previous definition, defer to the larger species that provides more benefits such as shade, soil moisture, and nutrients. For example, if a saguaro is under a AMDE4 and then a PAMI5, the PAMI5 would be recorded as the nurse plant. Dead nurse plants are still recorded, but their condition should be noted.

Noting Ailments

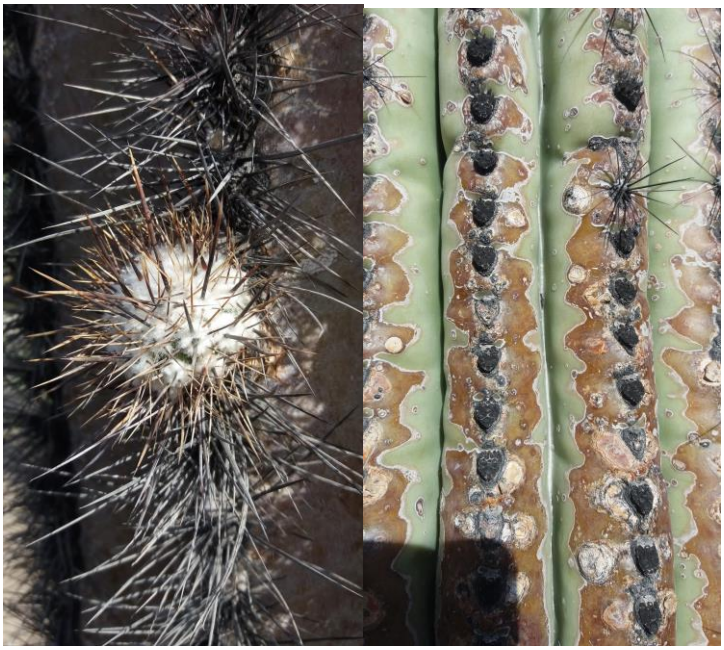
Physical damage such as girdling, scarring, decapitation, and animal cavities should be recorded for each individual saguaro. Similarly, signs of infection typically portrayed by discoloration, decomposition, and brittleness, should be recorded. Damage to growing tips, crowns, and other notable features such as nests and cresting are also of importance.


Left: Saguaro Crest. Right: bacterial infection (bacterial necrosis)




Left: sub-arm and dead arm example. Right: young Saguaro, <4” tall with discoloration

Left: Older serving as nurse plant. Right: bird nest in arms



Left: a nub, no discernable pleating so not included in count. Right: sunburns on an adult saguaro, not listed under ailments.

Appendix B - A Literature Review on Methodologies to Determine Saguaro Age

Population size, density, and age structure fluctuates significantly across the specie's spatial distribution (Pierson and Turner 1998). Important information regarding saguaro population dynamics can be discovered by analyzing the age class distribution of saguaro populations. Unlike many other tree species, saguaros do not put on annual growth rings. Scientists have learned that a saguaro's age can be estimated in relation to its height. However, the relationship between height and age varies between locations within the Sonoran Desert (Steenbergh and Lowe 1983). To accurately estimate the age of saguaros in the Sonoran Desert National Monument, the local relationship between height and age must be understood.

Interest in establishing height-age classes of saguaros in the Sonoran Desert increased when a noticed decline in populations sparked an effort to preserve the species. Examining the distribution of height-age classes within saguaro populations allows researchers to learn important information such as recruitment, survivorship, and mortality rate (Steenbergh and Lowe 1983). However, understanding the height-age relationship of a saguaro population is challenging. An individual saguaro exhibits varying growth rates throughout its life (Drezner 2006). Additionally, the average lifespan of a saguaro is 175 years, much longer than its human observer (Pierson et al. 2013). Areas where height-age classes have been established involved long and demanding processes. Some of the most detailed efforts took place in the Saguaro National Monument where researchers described crawling on hands and knees while using a magnifying glass to take the precise measurements needed to determine the relationship between growth and height.

Despite the inherent challenge, researchers have worked to develop height-age classes for locations throughout the Sonoran Desert. In the third volume of Ecology of the Saguaro, Steenbergh and Lowe define the height-age classes for two locations in the Saguaro NM (Saguaro National Park-East and Saguaro National Park-West) and also for the Oregon Pipe Cactus NM. In "An 85-Year Study of Saguaro (Carnegiea gigantea) Demography," Pierson and Turner focus on the height-age classes for Tumamoc Hill in Tucson, Arizona (Pierson and Turner, 1998). Turner later provided the height-age relationship for saguaros growing in McDougal Crater in Sonora Mexico (Turner, 1990). More examples exist, however, the results of these efforts are site specific, and are not meant to study population dynamics for saguaros growing elsewhere. Environmental factors such as topography, precipitation, seasonal temperature, and availability of microhabitats affect saguaro growth behavior. In fact, growth rate can vary by 100 percent or more between separate locations

(Drezner 2002). Therefore, the height-age relationship existing for one population will not necessarily be the same for those growing in other locations. This event is highlighted by the observed difference in growth rate found between studied locations even as close in proximity as Saguaro National Park East and West. Research finds that a saguaro that grows 10 centimeters one year in SNP-E, will only grow 7.43 centimeters in SNP-W (Drezner 2002). To accurately estimate the age of saguaros growing in the Sonoran Desert NM, a strong relationship between growth and height must be established.

Establishing a strong relationship between saguaro height and age has typically required an extensive amount of data; height measurements were taken annually for 436 known-age saguaros over an eleven year period to establish age-height classes in SNP-E. However, in most areas limited or absent saguaro growth data is more commonly the case. One researcher examining previously established age-height relationships suggests that defining the height-age classes in situations where annual growth data is limited can be problematic, pointing out that in Organ Pipe Cactus NM, where height measurements were taken for only 30 individuals once in 1967 and once again in 1977, "the relationship between growth and height is poorly established in some age classes (Drezner 2002)." Absent annual growth data will challenge the determination of age classes in the Sonoran Desert NM; the data collected in the initial year of this study will be the only existing height data. In her 2003 published work, Drezner attempts to address the problem of limited growth data with a method that allows researchers to determine height-age relationships more efficiently (i.e. without spending decades collecting site specific growth data).

While examining the growth curve models developed for established height-age relationships in separate locations, Drezner observed that although the growth rate varied, saguaro growth *pattern* was similar across locations. She proposed this similarity meant it was possible to approximate a *general* growth pattern that represents populations in all growth environments. The general growth pattern could be adjusted by an identified local growth factor to estimate the age of an unknown saguaro in a given location. Drezner demonstrates her theory by using the raw data collected in SNP-E to generate a linear equation for a general growth pattern. By quantifying the local growth factor for SNP-W and incorporating it into the general growth pattern equation, Drezner could produce the complete growth curve for the SNP-W population. The development of this method considerably cuts down the time and the effort required to determine the age-height relationship of a saguaro population. Only the value for the local growth factor is needed to produce a population's complete growth curve, which, theoretically, can be found by measuring the height of only one individual in any two separate years (Drezner, 2002).

The method Drezner provides may be useful for populations in the Sonoran Desert National Monument once monitoring is repeated; previously recorded saguaro growth and height data does not exist. Although age-height classes are defined in areas that could be considered climatically similar, research suggests it would be inappropriate to rely on them for data analysis within Sonoran Desert NM. Without this information, it is not yet possible to determine the true height-age relationship.

Although it is not currently possible to accurately estimate saguaro age in the Sonoran Desert NM, the initial height data collected might still be useful to investigate population dynamics. In their third volume of *Saguaro Ecology*, Steenbergh and Lowe discuss specific size related changes in growth form and function. They outline five size classes: young juvenile, juvenile, young adult, adult, and mature adult, each encompassing a height range corresponding to specific phenological events and physical characteristics (Steenbergh & Lowe, 1983). For example, a saguaro will begin to produce reproductive structures at approximately 200 centimeters, or once it transitions from a juvenile to a young adult. Analysis of the distribution of these size classes (i.e. the ratio of non-reproductive to reproductive classes) could help researchers learn important information for Sonoran Desert NM saguaro populations despite lacking defined height-age classes.

Literature Cited

Drezner TD. 2003. Saguaro (Carnegiea gigantea, Cactaceae) age-height relationships and growth: the development of a general growth curve. American Journal of Botany. 90(6): 911–914. doi:10.3732/ajb.90.6.911.

Drezner TD. 2006. Regeneration of *Carnegiea gigantea* (Cactaceae) since 1850 in three populations in the northern Sonoran Desert. Acta Oecologica. 29(2): 178–186. doi:10.1016/j.actao.2005.09.005.

Pierson EA et al. 2013. Regional demographic trends from long-term studies of saguaro (*Carnegiea gigantea*) across the northern Sonoran Desert. Journal of Arid Environment. 88: 57-69. dog:10.1016/j.jaridenv.2012.08.008.

Pierson EA. Turner RM. 1998. An 85-year study of saguaro (*Carnegiea gigantea*) demography. Ecology. 79: 2676-2693.

Steenbergh WF. Lowe CH. 1983. Ecology of the Saguaro III: growth and demography. National Park Service Scientific Monograph: Series No. 17. National Park Service. Washington, D.C.

Turner RM. 1990. Long-term vegetation change at a fully protected Sonoran Desert site. Ecology. 71(2): 464-477.